

SUPERCONDUCTING QUADRUPOLE FOCUSING LENS

Part II: Construction and Preliminary Tests

D.N. Cornish
U.K.A.E.A. Research Group, Culham Laboratory
Abingdon, Berks., England

I. INTRODUCTION

A quadrupole focusing lens is being developed using NbTi/copper composite superconductor. CERN, the Culham Laboratory and the Oxford Instrument Company are cooperating to carry out the work, which is also being partially financed by the Ministry of Technology. This paper discusses the problems associated with the superconductor, the general construction of the quadrupole, and preliminary tests on a test solenoid. The analytical design of the lens is described in the paper by Dr. A. Asner.

II. WINDING DETAILS

1. Selection of Superconductor

Since a high over-all current density is required in the winding if a worthwhile performance of the quadrupole is to be obtained, a fully copper stabilized winding is unsuitable for this application. The coil has been designed, therefore, to operate in the partially stabilized mode such that transient normalities, associated with short lengths of the conductor, will not result in a quench of the coil. To obtain this the heat transfer at the surface of the conductor has been limited to 0.4 W/cm^2 and cooling channels 0.01 in. wide have been provided between all layers.

From current density considerations, the optimum size of conductor would be a copper-clad 0.01 in. diameter NbTi wire, but the problems of winding a coil of this shape with such a small wire and preventing subsequent wire movements are very severe. A larger, rectangular conductor incorporating a number of superconducting filaments has therefore been used.

Details of the conductor, manufactured by I.M.I., are as follows:

Over-all dimensions	0.06 in. × 0.16 in.
NbTi superconductor	16 strands 0.01 in. diam
Operating current	820 A (at approx. 46 kG)
Copper resistance ratio	≥ 200:1 (H = 0)
Critical current	900 A at 50 kG
Conductor insulation	0.00075 in. thick Formvar

2. Interlayer Insulation

A specially manufactured nylon net is inserted between all layers to ensure that the two wide surfaces of the conductor are in contact with liquid helium. The net consists of 0.012 in. diam nylon monofilaments, spaced 16 to the inch, in a direction perpendicular to the direction of the winding, held in position by interwoven 0.0001 in.

diameter filaments. The woven net is calendered to an over-all thickness of 0.01 in. to increase the surface area in contact with the conductor. The over-all current density in the winding is 1.1×10^4 A/cm² with a conductor current of 820 A.

3. General Winding Details

Figure 1 is an illustration prepared from preliminary drawings to show the general arrangement of the quadrupole. The windings are wound on hollow formers fabricated from nonmagnetic stainless steel. Winding surfaces are insulated with resin-bonded glass fiber sheets with machined channels for liquid helium access. Part way through the winding the length of the layers is gradually decreased. These layers are supported by progressively inserting a thin steel plate, backed with stepped and channelled insulation, along the straight faces of the pole as the winding proceeds.

When the winding is completed a metal helmet is placed around the curved ends, with a small thickness of epoxy cast between it and the outside of the winding. To reduce the maximum field strength at the ends of the poles, the current density is reduced by inserting half-moon-shaped pieces of insulation between the layers at a number of points in the winding (not shown on illustration). Steel bands surround the four poles to restrain the windings against the outward radial electromagnetic forces.

III. TEST COIL

Before commencing manufacture of the first pole, a small test solenoid was wound to check the operation of the conductor in a thermal environment similar to that in the quadrupole. The coil parameters were as follows:

Inside diameter	1.0 in.
Outside diameter	4.37 in.
Length	3.94 in.

The anticipated load line of the quadrupole and that of the test solenoid are shown on Fig. 2. The solid (H-I) curve was obtained by multiplying the manufacturer's typical curve for a 0.01 in. diam wire by 16. The dotted curve has been drawn parallel to this through a single spot check point measured on a sample of the conductor used in the coil.

1. Tests on Solenoid

For the first series of tests the coil was mounted with its axis vertical. In all instances the coil was cooled to 77°K by heat transfer through helium gas to nitrogen outside the helium cryostat. The pressure in the vacuum chamber of this cryostat was raised to allow heat transfer to take place and it was repumped when cooling below 77°K was commenced.

When fully immersed in liquid helium the coil was energized and the current increased until it quenched. This procedure was repeated a number of times - the quenching value being 930 A on all occasions except the first which was 850 A. The coil was then remounted with its axis horizontal and the test repeated; the results of this series are shown on Fig. 3.

Since the minimum angle between the plane of the layer and the horizontal plane will be 26° on the quadrupole, the coil was then tested with its axis tilted at this angle. The coil was quenched many times, reaching the critical current on each occasion. The current through the coil was also reversed without affecting the quench value.

The final run in this series of tests was carried out with the coil horizontally-mounted exactly as on the previous occasion. The critical current was now reached every time.

2. Flux Jumping

A copper search coil had been wound on the outside of the test solenoid and its output signal was continuously recorded on a multichannel recorder during all the above tests. It is interesting to note the current at which signals were observed on this trace immediately prior to a quench during the second series of tests when the coil behaved erratically with the axis horizontal. The positions of the last few "flux jumps" have been shown for this series on Fig. 3. This trace also indicated that all quenches at 930 A, with the exception of run number 12, started with a smooth runaway whereas all the other quenches were initiated by a "flux jump."

3. Tests with Added Axial Pressure

The forces caused by the axial component of the magnetic field tend to expand the central turns of a layer more than the end turns where this component is weaker. The radial component of field produces axial compressive forces along the layers. It was thought possible that the signals observed on the pickup coil might have been triggered by interturn movement resulting from the radial pressure being released in jumps as the frictional force between turns was overcome. The coil was rewound after the weld holding one of the end checks to the form had been machined off and was now held to the form by three axial tie bolts. With the coil mounted vertically, its performance was checked by running it up to 915 A a number of times without a quench occurring. The tie bolts were then tightened such that the coil length was reduced by 0.025 in. There was no change in the signals on the pickup coil and the coil performance was unaltered. After tightening two bolts to their full extent, compressing the coil by a further 0.012 in., the brazing on the third bolt broke. The coil performance was again unaltered.

After repairing the tie bolt, further tests were carried out and, while the flux jump signals were unaltered, the coil behavior was erratic and quenched at currents between 500 and 810 A. Potential taps had been added to a number of the layers when the coil had been rewound and signals from these indicated that the quenches were being triggered by flux jumps and that the quench was propagating from varying points in the vicinity of the central layers. When the coil quenched at full current, it started in the inner, high field, region.

Subsequent examination of the coil showed that the PTFE packing at the ends of the layers had been axially compressed by the force of the tie bolts and this had resulted in a corresponding expansion in the radial direction between the interlayer nylon strands, thus partially blocking many of the cooling passages.

4. Conclusions from Solenoid Tests

The following conclusions are drawn from the results so far obtained on the test coil:

- a) The coil produces transient signals which appear to be caused by flux jumps and not by mechanical movement of the wiring or heating due to frictional forces.
- b) If the cooling passages are not blocked, the performance is unaffected by these disturbances and the critical current of the conductor is reached before the coil quenches.

- c) If the cooling passages are partially blocked, the energy associated with the flux jumps is sufficient to cause the coil to quench prematurely. In these cases normality is initiated in a low field region.

The behavior of the coil when tested horizontally suggests that the cooling ducts were partially blocked the first time but that the blockage was cleared for subsequent tests.

- d) The current interval between flux jumps appears to be related to the probability of quenching at a flux jump. Above about 700 A, in most cases, if the current interval between jumps is not greater than 60 A then the coil will not quench until the critical current is reached. If, however, the current is increased by more than this amount without a flux jump occurring, it is probable that the next flux jump will initiate a quench.

IV. PRESENT POSITION OF QUADRUPOLE

The first pole has now been wound and it will be tested in the near future.

Note added by the Editor

We have received from Mr. Cornish a letter dated August 30, 1968 which includes the following information:

"The design current for the whole magnet is 820 A giving a field gradient of 5.5 kG/cm. The first pole has now been tested and the current was raised to 1000 A without quenching. The maximum value of field at this current was approximately 50 kG.

"We are very satisfied with this performance and thought you might be interested in the result."

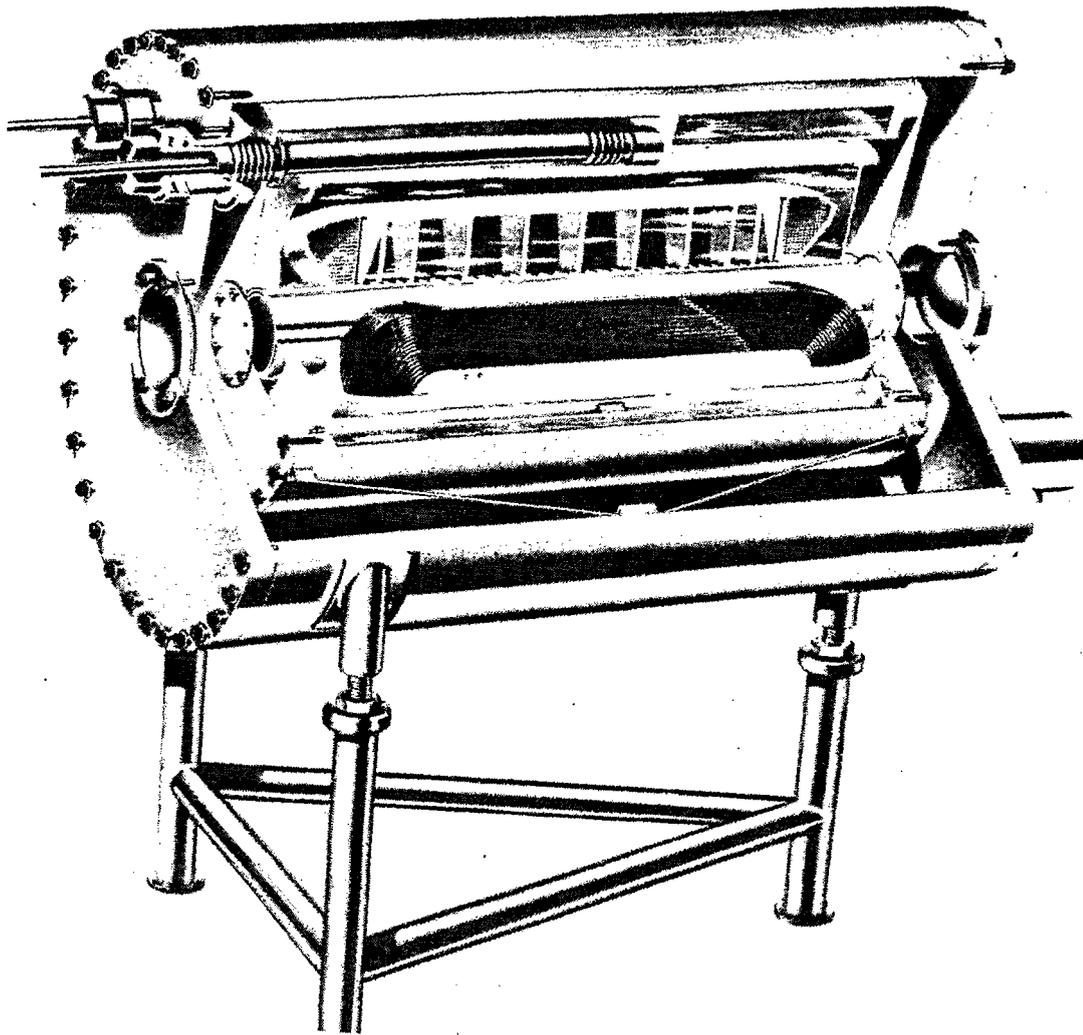


Fig. 1. Superconducting quadrupole focusing lens.

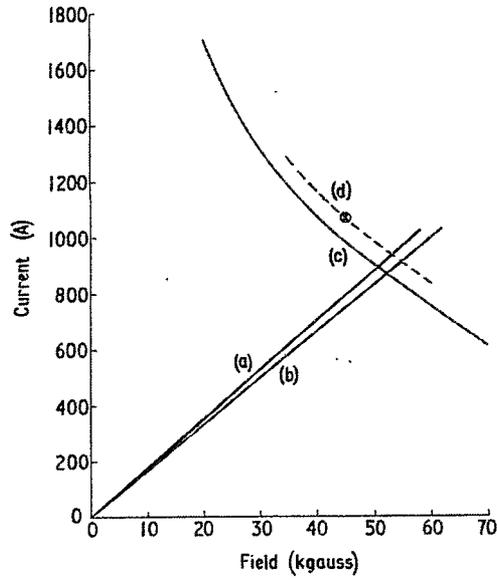


Fig. 2. (a) Load line of maximum B in quadrupole.
 (b) Load line of maximum B in test coil.
 (c) Typical critical current.
 (d) Curve through measured point on critical curve.

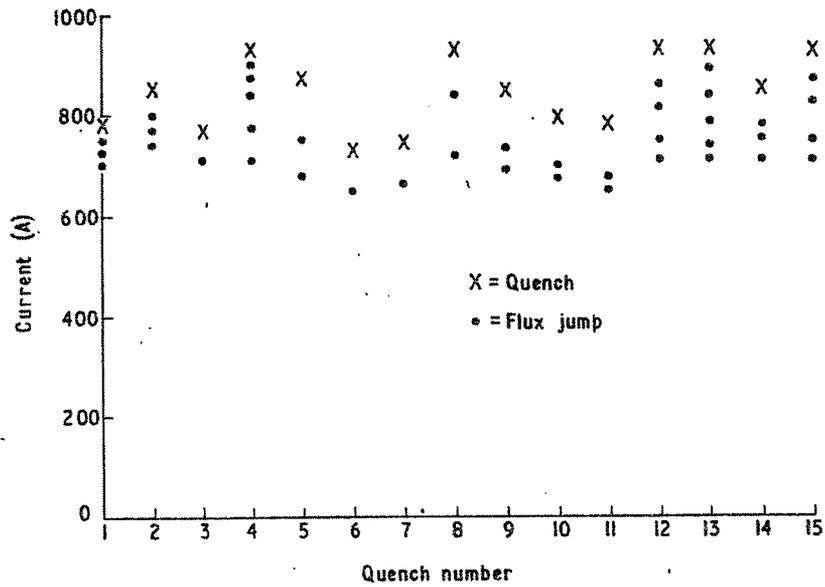


Fig. 3. Quench and flux jump currents with test coil mounted horizontally.